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## APPENDIX B: ANALYSIS OF A STAGE-STRUCTURED MODEL

The results presented in the main text are based on a model that lacks stage structure. Here I investigate the robustness of these results to stage structure. To this end, I develop a stage-structured IGP model that incorporates intra-specific interference and a temporal refuge in the IGPrey. The resource has three stages: eggs ($E$), juveniles ($N$) and adults ($A$). The two consumer species each have juvenile ($L_i$) and adult ($P_i$)($i = 1, 2$) stages. I consider both consumers as attacking the egg stage of the resource, because it causes the most delay in converting consumption into reproduction and thus provides a more restrictive case for coexistence than attacking the juvenile stages. Attacking different stages in itself does not lead to coexistence (Murdoch *et al.* 2003). Consumer species 1 is superior in resource competition but consumer species 2 can prey on or parastize larvae of consumer species 1. Thus, consumer 1 is the IGPrey and consumer 2 is the IGPredator. The dynamics of the community are given by:

Refuge period (resource and IGPrey) ($0 \leq t \leq T_R$)

$$\frac{dE}{dt} = rA - m_E E - a_1 E P_1 - d_E E$$

$$\frac{dN}{dt} = m_E E - qN^2 - m_N N - d_N N$$

$$\frac{dA}{dt} = m_N N - d_A A$$

$$\frac{dL_1}{dt} = e_1 a_1 E P_1 - m_{L_1} L_1 - d_{L_1} L_1$$

$$\frac{dP_1}{dt} = m_{L_1} L_1 - d_{P_1} P_1$$

Non-refuge period (Resource, IGPrey, IGPredator) ($T_R \leq t \leq T$)

$$\frac{dE}{dt} = rA - m_E E - a_1 E P_1 - a_2 E P_2 - d_E E$$

$$\frac{dN}{dt} = m_E E - m_N N - d_N N - qN^2$$

$$\frac{dA}{dt} = m_N N - d_A A$$

$$\frac{dL_1}{dt} = e_1 a_1 E P_1 - m_{L_1} L_1 - \alpha_{11} L_1 P_1 (1 - f_{f11}) - \alpha_{12} L_1 P_2 - d_{L_1} L_1$$

$$\frac{dP_1}{dt} = m_{L_1} L_1 - d_{P_1} P_1$$

$$\frac{dL_2}{dt} = e_2 a_2 E P_2 - m_{L_2} L_2 - \alpha_{22} L_2 P_2 (1 - f_{22}) + f_{21} \alpha_{12} L_1 P_2 - d_{L_2} L_2$$

$$\frac{dP_2}{dt} = m_{L_2} L_2 - d_{P_2} P_2$$

The parameter $r$ is the per capita rate of resource reproduction, $q$ is the strength of resource self-limitation, $m_E$ is the resource egg maturation rate, $m_N$ is the nymphal/larval maturation rate, and $d_X$ is the density-independent mortality rate of stage $X$ of the resource. The parameter $a_i$ is the attack rate of consumer $i$ on resource eggs ($i = 1, 2$), $\alpha_{12}$ is the attack rate of consumer 2 on resource eggs previously parasitized by consumer 1 that contain larvae of consumer 1 (IGP), and $\alpha_{ii}$ is the attack rate of consumer $i$ on resource eggs parasitized by other conspecific females (intra-specific interference via cannibalism or superparasitism). The parameter $e_i$ is the number of consumer $i$ offspring resulting from resource consumption, $f_{ji}$ is the number of consumer $i$ offspring resulting from IGP $(i, j = 1, 2, i \neq j)$, and $f_{ii}$ is the number of consumer $i$ offspring resulting from intra-specific interference. The parameters $m_{L_i}$, $d_{L_i}$ and $d_{P_i}$ are, respectively, the juvenile maturation rate, the juvenile mortality rate and the adult mortality rate of consumer $i$.

Since the model does not lend itself to analytical results, I numerically simulated long-term dynamics for 365,000 time steps (corresponding to a time span of 1000 years) using the method of Runge-Kutta step 4 (Press *et al.* 2001). Figure B1 illustrates the influence of key parameters on mutual invasibility, while Fig. B2 illustrates the long-term species' abundances under various combinations of mechanisms.

Overall, the stage-structured model yields similar outcomes as the unstructured model. Stage structure has a small effect on intra-specific interference in that the productivity range for coexistence is increased above that in the unstructured model. Stage structure has no influence on the refuge's effect on coexistence. This is to be expected because intra-specific interference is the mechanism for which stage structure is important. The overall similarity in the conclusions suggest that stage structure in itself is unlikely to alter the effects of interference or a refuge on the coexistence of IGPrey and the IGPredator. However, the model considered here contains constant maturation rates and thus ignores the delays in the development of larval and adult stages of IGPrey and IGPredators. Whether such delays influence the operation of multiple coexistence mechanisms needs to be investigated.

## LITERATURE CITED

Murdoch, W.W., C.J. Briggs, and R.M. Nisbet. 2003. Consumer-resource dynamics. Princeton University Press, Princeton, New Jersey, USA.

Press, W.H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling. 2001. Numerical Recipes in C: The Art of Scientific Computing. Cambridge University Press, Cambridge, UK.

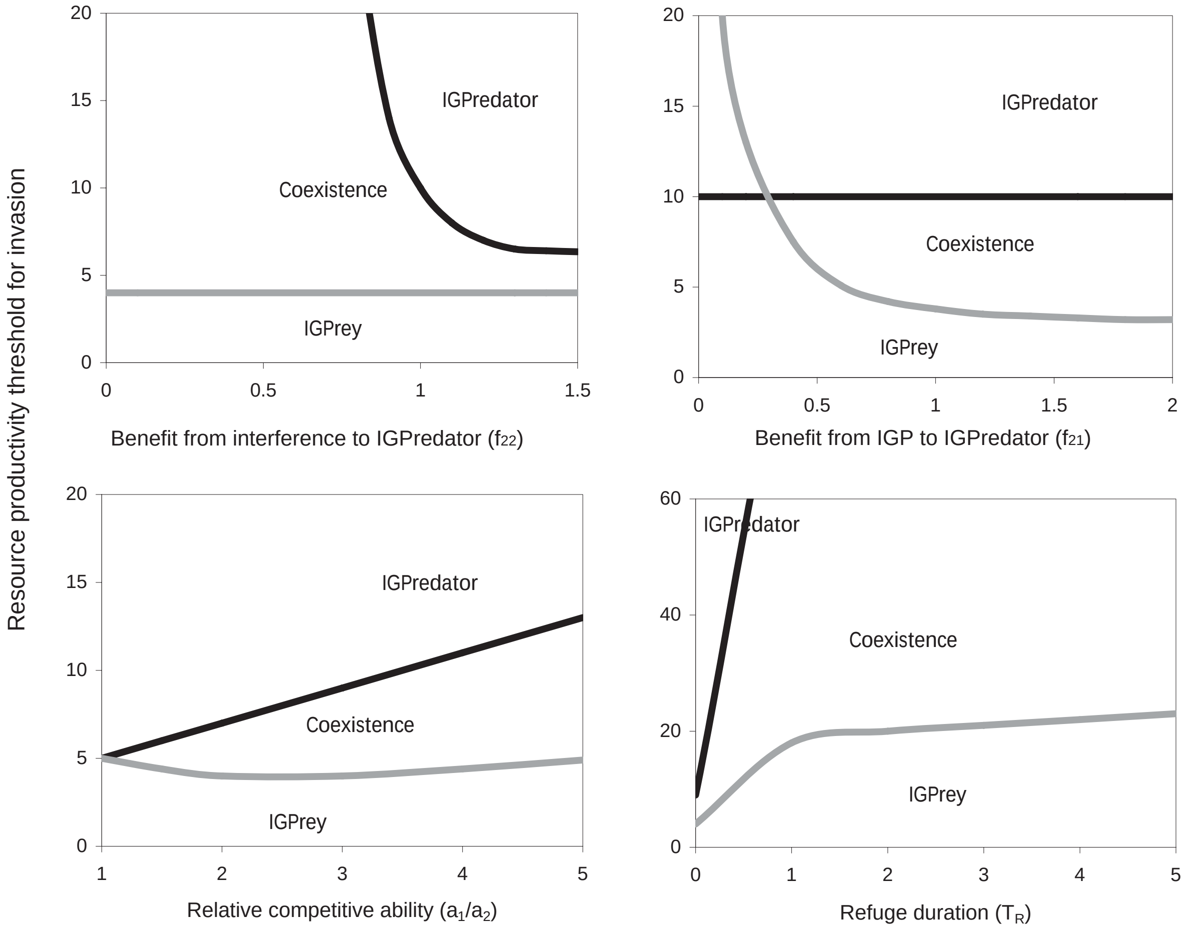


Fig. B1: The impact of key biological parameters on the IGPrey and IGPredator's invasibility (threshold resource productivity required for invasion) in the stage structured model (Appendix B). The black line is the invasion boundary for the IGPrey, and the grey line is that for the IGPredator. The IGPrey can invade at productivity values below its invasion boundary, and the IGPredator can invade at productivity values above its invasion boundary.

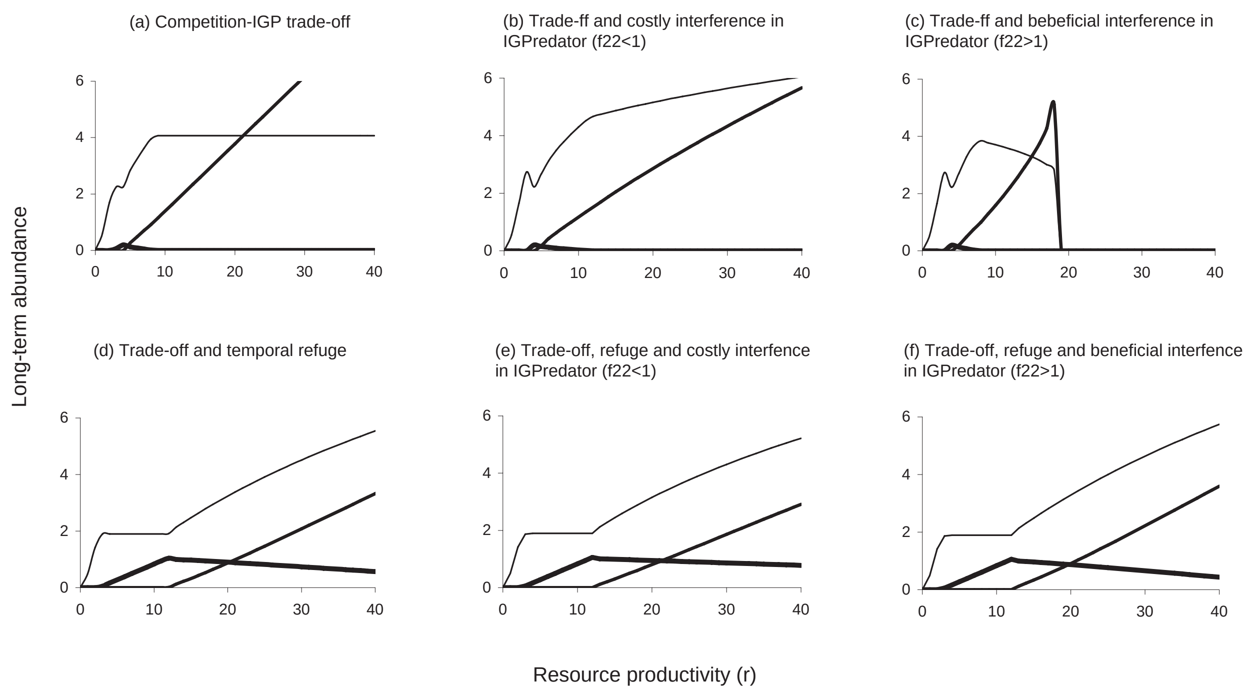


Fig. B2: Long-term abundances predicted by the stage-structured model (Appendix B) as a function of resource productivity. Lines of increasing thickness depict respectively, the abundance of the resource, IGPredator and IGPrey. Parameter values used are: $a_1 = 6, a_2 = 2, \alpha_{12} = 2, \alpha_{22} = 2, e_1 = 1, e_2 = 1, f_{21} = 2, f_{22} = 0.9$ (costly inteference), $f_{22} = 1.05$ (beneficial interference), $m_E = 1.8, m_N = 0.8, m_{L_1} = 0.8, m_{L_2} = 0.8, d_E = 0.2, d_N = 0.2, d_A = 0.33, d_{L_1} = 0.2, d_{L_2} = 0.2, d_{P_1} = 33, d_{P_2} = 33, q = 2, T_R = 4$ and $T = 12$. These parameters reflect an IGP community with an invulnerable adult stage of the resource species that is long-lived compared to its juvenile stages, and IGPrey and IGPredator adults that are short-lived relative to their larval stages. These features capture the biology of many insect communities, paricularly parasitoid guilds. These parameter values also depict the worst-case scenario for coexistence in resource-rich environments: the IGPredator receives the same reproductive benefit from the basal resource as does the IGPrey ($e_1 = e_2$), and gains a large benefit from consuming the IGPrey ($f_{21} > e_1$).